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Towards a Sustainable Front-End of Nuclear Energy Systems

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Mined out open-cast uranium mine at Arlit, Niger (WEF)

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EXECUTIVE SUMMARY

The purpose of the report is to map out areas of further research that will help to better assess the viability of uranium (and thorium) as a source of energy. The report discusses sustainability issues related to the so-called 'front-end' of the nuclear fuel cycle, which is defined here as to comprise the exploration, the mining and milling of uranium and thorium ores, not forgetting the long-term management of residues arising from these processes. Demonstrating an optimal use of resources with minimal environmental impact will help to increase the public acceptability nuclear energy systems. The processes of enrichment and fuel fabrication are not subject of this report.

The viability of current once-through fuel cycle fission-based nuclear energy systems is hinged on the availability of uranium, or thorium, as fuel and on the question whether the overall energy balance of the respective fuel cycle is positive, taking into account the full life-cycle energy costs. The fundamental question thus is: how much (fractional) energy units do we need to invest in order to produce one energy unit in a useable form, i.e. as heat or electricity.

Uranium is a fairly common element in the earth's crust, but mineable concentrations do not occur too frequently. Comparison with historic mining data for gold and silver leads to the expectation that uranium reserves could increase by orders of magnitude over what is known today, if the same investment into exploration would be made that has been historically made for these precious metals. Resources estimates are commonly made on the basis of economic cost to recover the resource. From a global energy supply sustainability point of view, neither commercial nor national strategic considerations, nor time considerations are really relevant. As oil prices have shown, society can and will accommodate price increases by one order of magnitude over the span of half a century.

In addition to conventional ores, a number of so-called 'unconventional' uranium sources have been identified, such as phosphate minerals, residues from coal burning and the seawater. Some of these exceed in quantity by far the 'conventional' resources. The energy efficiency of utilising these potential resources is strongly debated in some cases, but very few hard data exist yet. Hence,

- possible energetic synergies between various processes, such as sea-water desalination or fertiliser production, and the recovery of uranium should be investigated;
- a quantitative database of which (historical) process residues might be amenable to uranium recovery needs to be drawn up.

The individual process steps that lead from the undiscovered resource to 'yellow cake' as the marketable uranium product are well established, but the energy costs and associated greenhouse gas (GHG) emissions are not very well known in quantitative terms. Hence,

- detailed, actual industry data for process energy or life-cycle energy costs should be compiled for the various components of exploration, mining and milling of different rock types;
- possible scenarios, technical feasibilities and logistics for low-carbon energy supplies to uranium mines and mills could be explored together with the relevant producers.

In summary, it is concluded that a comprehensive assessment of the full-life cycle energy costs of uranium/thorium mining, milling and subsequent decommissioning and remediation of the related infrastructure is required. This assessment needs to be based on real industry data and should comprise both, conventional uranium mining and the utilisation of the so-called unconventional resources. The SNETP consortium would provide a good starting point, as it comprises most of the major players of European relevance.

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Introduction

This report is not about what should or should not be done, but what could and can be done. This report is also not about finding <u>the</u> solution, but about assessing the prospects of uranium as an energy source within a mix of energy systems. It is striving not to be biased by the concept of market-driven public policy decision making. The purpose of this report is to increase the overall utility of nuclear energy systems by addressing utility issues of the front end of the nuclear fuel cycle.

Primary energy sources

Sources of primary energy are a fundamental need of human civilisation and it is useful to put nuclear energy systems into the appropriate overall context. A simple to-the-root analysis shows that there are only four basic sources of energy available to us: solar radiation (due to nuclear fission and fusion), artificially-induced nuclear fission, the geothermal flux (which is due to radioactive decay in the earth's crust and mantle) and the earth's rotational energy in combination with gravity. They are listed in their current relative importance. At some stage in the future it may also be possible to harness nuclear fusion.

The analysis to-the-root shows that all fossil fuel-based and so-called 'renewable' energy systems, such as those harnessing wind, water and bio-fuels, rely on solar radiation as the primary source of energy. They are merely systems that store energy a form that is convenient to use. Thus both, fossil and bio-fuel systems are based on photosynthesis or similar processes that reduce atmospheric carbon dioxide to carbon. Solar radiation is also responsible for the mass movements within the atmosphere that we experience as wind and utilise in windmills. Solar radiation evaporates water that is then transported to mountain regions, where it condenses and precipitates; we then can utilise the potential difference between these elevated regions and the sea as 'hydro-power'.

An immense amount of energy is stored in the hot earth's interior. It is constantly lost to space and in consequence a geothermal gradient downward from the earth's cool surface can be observed. Geothermal energy systems tap into this resource by circulating underground water or steam as a heat carrier.

The earth's rotational energy can be tapped into by harnessing it as tidal wave energy.

Nuclear fission-based energy systems rely on a sustained, but moderated, chain-reaction that induces fission of fuel atoms (e.g. ^{235}U) by absorption of neutrons, which in turn generates more neutrons, etc.

There are two fundamental conditions that control the usability of any of the above energy systems: a) whether the overall energy balance of its utilisation is positive and b) whether it can deliver energy in a useful form at the time and location where it is needed. However, sometimes condition (a) is violated because a certain type of energy carrier is needed at a certain place and time, but cannot be substituted. Generally these choices are made by societies without scientific reasoning and on the basis of expedience and short-term preference only. The following is intended to provide a more scientific basis for making such choices with a view to achieve utility at a grander scale.

Decision making on energy systems

Today, decision making in energy policy is still dominated by considerations of economic competitiveness and short-term profits. While this encourages the use of fossil fuels, the need to move away from carbon-oxidising to other types of energy systems is being recognised, but the alternatives remain controversial. Nuclear energy systems are being promoted as likely to be able to play a substantial role in avoiding carbon emissions (IAEA, 2006f).

Nuclear energy systems, however, can and do have effects (thermal, radiation, chemical and physical) on the environment under normal operation. The main impacts have arisen in the past at the front-end of the fuel-cycle, namely uranium or thorium mining and milling, and at the back-end from poorly managed radioactive waste (excluding spent nuclear fuel and high-level waste that are managed well). Severe accidents during power plant operation and their impacts remain a public concern though. In choosing energy options, perceived environmental and health impact, and hence the lack of acceptance, has been recognised as one of the critical issues for the development of nuclear energy systems (IAEA, 2003b). This is in stark contrast to the actual environmental and health impact arising from e.g. fossil fuel-based energy systems. If it can be demonstrated that environmental and health impacts can be kept within acceptable limits, together with other critical factors (such as cost, safety including waste safety, resources availability and supply security, proliferation risks) the nuclear energy option has a potential to be further deployed and accepted by society and industry.

The present report discusses the sustainability of using uranium as a fuel in nuclear energy conversion systems with respect to the energy balance within the system and the availability of uranium ores.

Analysing sustainability

Defining the system

Sustainability as a concept still remains somewhat vague, but numerous efforts have been undertaken to better define the conceptual approaches and (semi-)quantitative measures. Thus, for instance, sets of indicators have been developed that *inter alia* cover aspects such as 'exhaustion of resources', 'production of non-degradable waste' and 'societal impacts' (e.g. KRÖGER, 2001; IAEA, 2003b).

Assessing any energy system with respect to its sustainability requires first of all appropriate system boundaries to be drawn. How and where such boundaries are drawn depends on the purpose of the assessment, on the underlying conceptual system model and also often on the political or ideological intentions. Unfortunately, the results of any sustainability or life-cycle (impact) assessment can be tweaked into a way that supports the intention of those who undertake or commission such assessments. Different choices of boundaries can dramatically change the conclusions that can be drawn. System boundaries in consequence are often drawn to exclude or include aspects that may make the system under investigation appear good or not so good respectively.

The fundamental question for such assessments is: how much (fractional) energy units do we need to invest in order to produce one energy unit in a useable form, i.e. heat or electricity. In other words: what is the energy cost of providing 1 Joule worth of fuel for oil/gas/coal/nuclear/ biofuel-based energy conversion systems ? Closely related to this question is the question, whether the energy content of the ore/fuel to be considered in life-cycle energy balances.

Energy conversion systems in industrial societies are highly complex and have global interrelations. All three major groups of energy conversion systems, fossil fuel-based, renewables-based and nuclear, rely on the same industrial infrastructure and supply chains. Therefore it is rather difficult to delineate the individual systems for the purpose of a LC(I)A. There is also the aspect of economy of scale and conversely a minimum number of individual systems to make the nuclear energy system as a whole viable. It would be clearly not possible to have the highly complex nuclear fuel cycle facilities supplying only one or even a few nuclear power plants. One has also to consider whether and how, for instance, the energy embedded in the supporting infrastructure and the labour expended is to be treated in a holistic analysis.

As the overall objective of such LCAs is the evaluation of different energy systems with respect to their sustainability in every respect, the same kind of boundaries must be defined for all systems in order to make them comparable. Like must be compared with like. **More conceptual research with a view to arrive at a fair treatment of all energy conversion systems is needed.**

Unlike for many other energy conversion systems, the whole life cycle of the infrastructure of nuclear energy systems is being considered early on during the project due to the inherent risk of radiological contamination. Hence provisions are made for decommissioning and waste management. While such provisions are made in principle, to date only a few plants have gone through the full life cycle. Also, final waste management solutions for high-level radioactive waste coming out of nuclear power programmes have not been implemented yet. The objective is the internalisation of all (societal) costs and environmental effects.

The internalisation of these costs and effects leads to considerable debate, as not only the question of delineation of the system arises, but also of the acceptability of environmental changes. The latter is largely an ethical question and will be answered differently by different groups of stakeholders. Several key questions, for instance, are:

— to which standards the environment needs to be remediated after the closure of uranium mines and mills and following the decommissioning of nuclear facilities,
— which provisions need to be made for the long-term management of near-surface disposal sites,
— whether near-surface disposal of mining and milling residues is acceptable at all.

In this context it may be repeated that energy conversion systems other than nuclear may also generate residues with a considerable radionuclide content, but typically are not subject to the same stringent remediation targets when being decommissioned. A comprehensive discussion of environmental remediation of uranium mining and milling facilities can be found for instance in IAEA (2002b,2006c). The effect of extreme remediation targets on the energy balance, namely, when all residues are to be back-filled into the mine and sites are to be remediated to 'greenfield' targets can be seen in the calculations by STORM VAN LEEUWEN & SMITH (2008). DONES (2007) provides a more realistic scenario, but is somewhat less comprehensive due the lack of real data.

While the front end and the back end of the nuclear fuel cycle has drawn considerable attention by stakeholders due to various contentious issues, it is not clear to what extent the front and back ends of other energy conversion systems undergo the same kind of treatment. Are, for instance, the overseas mines from which coal is imported into Europe remediated to the same standards as is expected for uranium mines ?

While the discussion has focused on the energy costs and associated emissions, in particular of GHGs, it should be remembered that any energy conversion system has a wide range of impacts on the environment. Thus one may be also interested in the specific footprint, i.e. the area occupied by the various installations, the various energy conversion systems have per Joule net energy produced. This footprint should include those areas that are temporarily or permanently occupied or devastated by system components, such as mine head-frames, ore/coal storage areas, sorting or milling plants, transfer stations, refineries, boiler or reactor houses, turbine house etc. It should also include areas dedicated to the disposal of mining, milling and other process residues, such as tailings or (fly) ashes. While the respective delineation of such areas is rather straightforward for some systems, it becomes more difficult and contentious for others. Thus it is certainly not sufficient to define as 'footprint' for wind power installation just the area of their foundations. **Further research appears to be necessary to determine methods for a fair assessment of the life-cycle footprint of energy conversion systems.**

Global distribution of costs and benefits

The seemingly unequal distribution of costs and benefits in both senses, geographical and time, that arise from mining operation has become a point of contention in more recent years in the assessment of resources use in general and of energy systems in particular. This geographical inequality is due to the fact that most mining (not only uranium mining) today occurs in third-world or emerging economy countries, while materials and energy are largely consumed in the developed world. Thus it is estimated that 70% of the World's uranium resources are located beneath lands inhabited by indigenous peoples in Africa, Asia, Australia and the Americas (PRESTON & BARUYA, 2006). The (perceived) inequality in time arises from the notion that environmental and health costs have to be borne by generations that follow the one consuming the materials and energy. However, this is a rolling 'problem' and one that has being going on since the beginning of man-kind. Succeeding generations always benefited from the technological and economical advancements brought about by the consumption of materials and energy. This is, of course, not meant to deny the built-up of considerable legacy costs in some geographical areas and environmental compartments.

Society will attach different values to different forms of energy. Society makes *inter alia* choices as to whether an energy (sub-)system is acceptable, even so it may incur an overall negative energy balance, because it renders energy in a desirable form. This negative balance has to be then compensated for by other energy conversion systems. A point of criticism is that these energy balances (and associated environmental impacts) are not necessarily even for a given society. Rather, there are societies with largely negative balances and societies with positive balances. The societies concerned may be located on different parts of the globe.

While the environmental (and health) impacts and costs from life-cycle emissions and wastes are important criteria for the sustainability of all energy system, this study focuses on their energy balance. The economics of any energy conversion system are important for determining its viability within a given local, regional or global economic context. Though return of investment and similar criteria are relevant business decision making criteria, these may be insufficient for long-term strategic planning considerations for humanity. Not every solution that is economically viable today will stand up to long-term sustainability assessment. 'Markets' will not necessarily solve supply problems from a sustainability point of view. For this reason 'cost' is not necessarily considered a useful criterion in this study. Economically acceptable costs have to be always seen in the context of long-term demand scenarios and possible alternatives.

The choice of energy conversion system and fuel will also be strongly influenced by the fact that often the consumption location is not the same as the location of the primary resource. Thus fuels are often imported into the 'developed' world or the regions with abundance of sunshine are not necessarily the same as the industrialised ones, which are typically are in the temperate regions of the world.

The debate over potentially exhausting resources of certain natural materials and energy carriers, over the concurrent environmental impacts, including global warming, and over possible countermeasures seems to indicate that the great majority of humans are not prepared to exercise self-constraint. Self-constraint and true market economy appear to be mutually exclusive concepts. True market economy has an inherent tendency to utilise more and more resources, including energy. The rising awareness that unrestrained use of resources has led to and will lead to further undesirable consequences prompted the interference of policy-makers in a variety of ways. As has been shown (e.g. HANLEY *et. al*., 2008) that such interference, typically by providing incentives, such as subsidies, or penalties, such as penalties on emissions, has only limited effects in time. In addition, such interference with particular aspects of the energy conversion system can have rather unforeseen effects within the regional or global economic system as recently exemplified by food crop shortages due to positive incentives given to growing crops as biofuels or the predicted increase in energy use in the wake of providing incentives to improve energy efficiency (HANLEY et al., 2008).

Life-cycle management of nuclear energy systems

Overview

All human activities result in flows of material and energy, which in turn bring about changes in the respective environment. Life-cycle management (LCM) and life-cycle impact assessment (LCIA) are responses to a change in paradigms whereby undesirable environmental changes are being anticipated and avoided, rather than treated after they have occurred. The LCM approach aims to treat each stage in the life of a process or facility not as an isolated event, but as one phase in its overall life. Materials flow accounting (MFA) was developed as a tool for LCM from the 1970s onward, stimulated by the fear of essential resources becoming depleted on a country or even a global scale. The tool later was used for other purposes too, such as the identification dispersive losses to the environment of harmful chemical substances, e.g. heavy metals, and to reduce or phase out their use (EUROSTAT, 1997).

Every human activity has a range of life-cycle 'costs' associated with it (Figure 1). Traditional costing approaches normally take into consideration the so-called 'conventional costs' only, i.e. direct and indirect costing items that cannot be avoided by undertaking a certain project: capital costs, equipment, energy, utilities, supplies, etc.
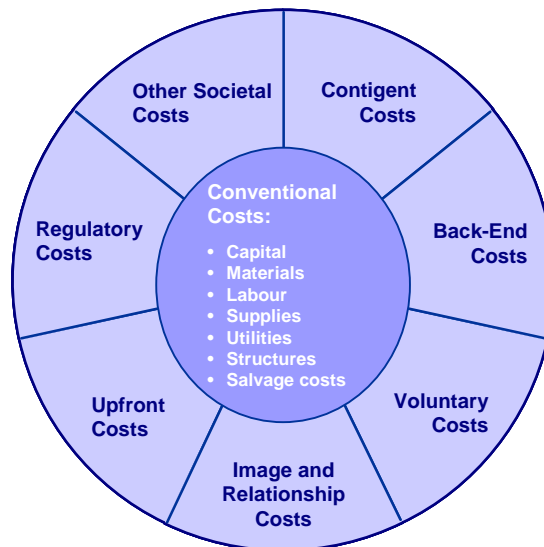

Figure 1: Life-cycle costs

Life-cycle management requires the adoption of broader costing concepts in which all costs involved in the implementation of the project, from the initial planning phase to the decommissioning and stewardship phases have to be taken into account (IAEA, 2002b). A more detailed overview over the nuclear fuel cycle and a current world-wide list of fuel cycle facilities can be found in Nuclear Fuel Cycle Information System (NFCIS; IAEA (2009). Figure 2 gives a brief generic overview of the life-cycle of such facilities.

Optimal use of non-renewable (natural) resources and minimisation of waste generation are essential goals to enhance sustainability of nuclear energy systems and has economic benefits. Conceptualising and quantification of material and energy flows is a prerequisite for minimising the use of resources. It is obvious that by reducing or eliminating particular flows the related environmental impact will be reduced. Alternatively, for flows of a certain material or energy conversion techniques that cause significant impacts, there may be an option to replace them with more benign alternatives. Demonstrating an optimal use of resources with minimal environmental impact will help to increase the public acceptability nuclear energy systems (IAEA, 2003b).
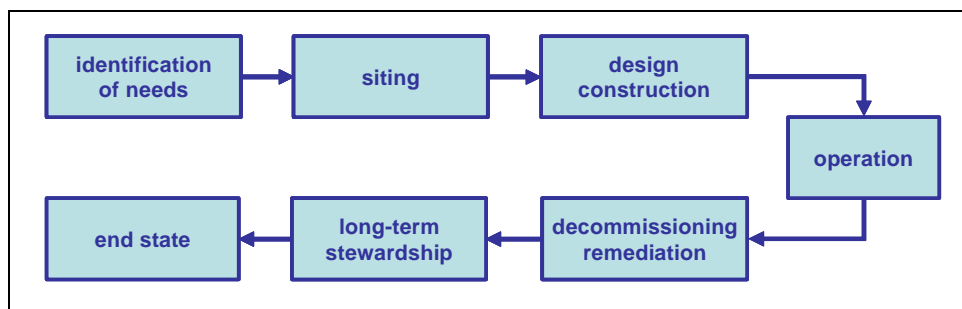
Figure 2: Generic life-'cycle' of a nuclear facility.

There have been quite a number of (partial) life-cycle assessments for nuclear systems in the past (e.g. JANSMA & VAN GEMERT, 2001; DONES, 2007) and these were recently critically reviewed by SOVACOOL (2008). His main interest was in greenhouse gas emissions, but the reflections with respect to their quality apply to other aspects of the life-cycle cost of nuclear energy systems as well. **SOVACOOL (2008) noted that only 19 out of the 103 studies identified would in fact provide useful and transparent information. There is clearly room for further development**.

Assessing Materials Flows

The basis for any LCA is a materials flow assessment (MFA) that consists of assessing, where and how much of a particular substance, or energy enters or leaves an environmental compartment, an (industrial) process, and where it appears in products, intermediates, residues and wastes. MFAs can be undertaken at various scales, ranging from single plants to whole countries. Figures 3 and 4 are simplified examples for the likely material flows associated with a uranium mine and mill respectively. As a matter of fact, many industrial operations routinely apply MFA techniques to manage and control their materials requirements during the production process and to identify the potential for reducing wastes and emissions.

Energy balances

Similarly, the flows of energy within a system or its subsystems can be assessed and each material flow depicted in Figures 3 and 4 has also an energy flow associated with it. IAEA (1994), for instance, provides a comprehensive treatment of the subject in principle. In recent years, the definition of what constitutes an 'overall' energy balance has become the focus of much scientific, political and ideological debate. There is a considerable divergence of views, whether particular energy conversion systems are net energy producers or not, i.e. whether the sum of all inputs and losses is smaller than the sum of the useful output (Figure 5). The question is complicated by the fact that our energy conversion systems have developed since the beginning of man-kind and all carry with them a burden of legacies, but also of endowments. In addition, many energy conversion systems coexist at any given time and provide input to each other. Our energy conversion systems are highly integrated. Therefore, it becomes conceptually intractable to attribute energy uses and environmental burdens to specific conversion systems as a whole.

While such an analysis would be relatively straightforward in undeveloped societies that may rely on only one primary fuel, e.g. collected wood, it is a very complex procedure for the highly integrated modern industrial societies. Here, different fuels and different energy systems complement each other, even to the point where condition (a) from above is violated in order to obtain for instance a particular type of fuel. Thus hydropower might be used to produce the electricity that is needed at some distance away to operate a mine that produces the coal that is needed in the making of steel that is needed to make well-field equipment for the production of natural gas which in turn is burnt in power plants that generate electricity somewhere else.
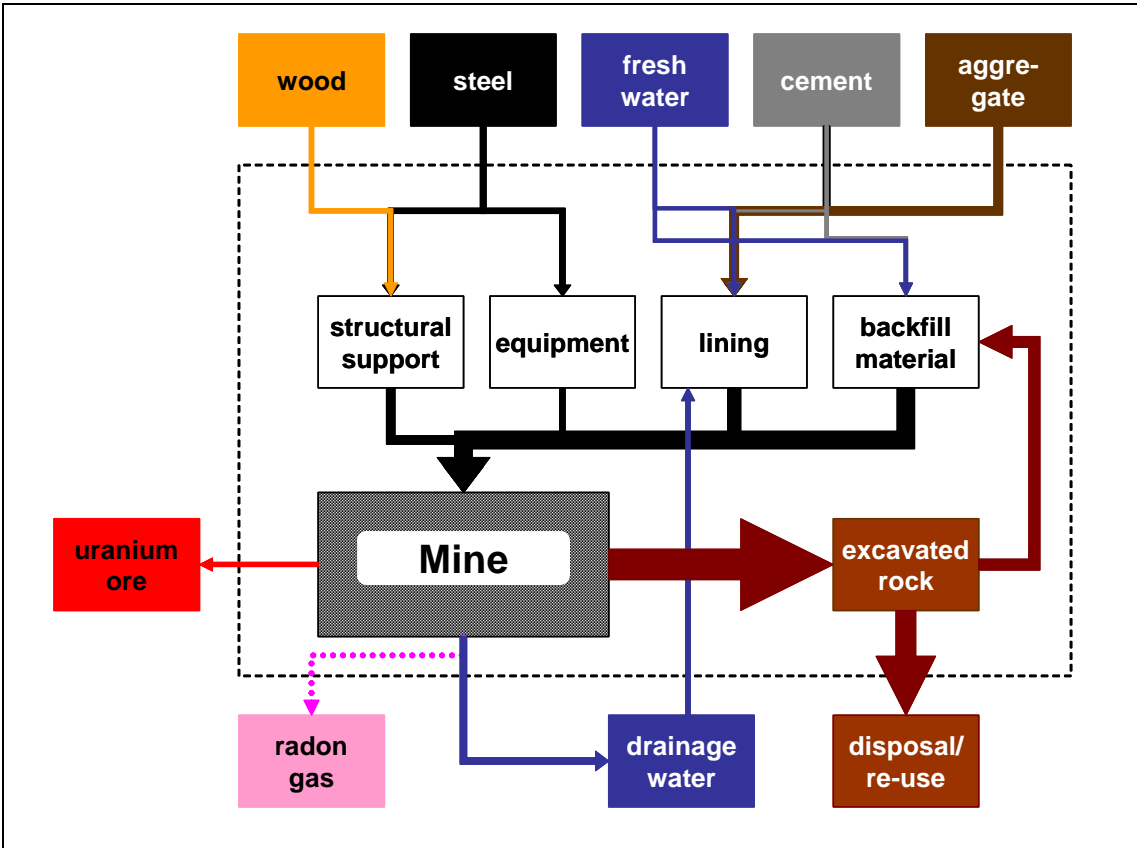
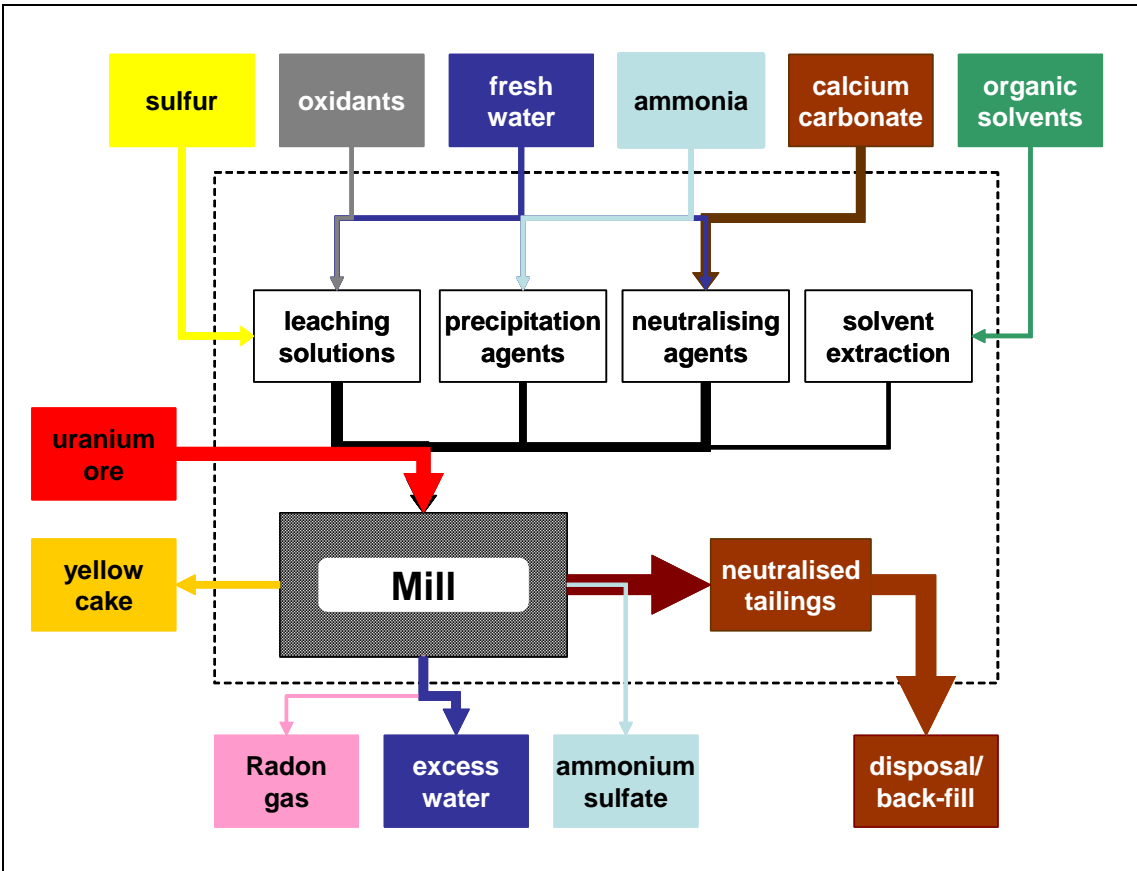**Figure 3**: Simplified example of material streams in an uranium mine.

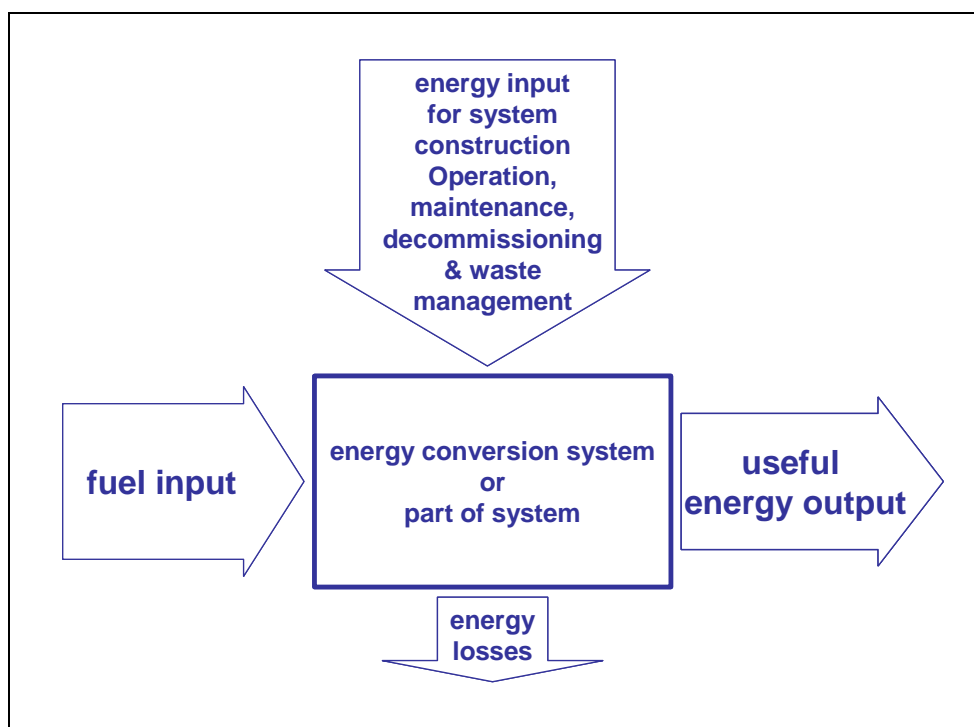**Figure 4:** Simplified example of material streams in an uranium mill.

Figure 5: Input-Output analysis in an energy conversion system or parts of it.

With such scenarios – that are real - it becomes very difficult to draw boundaries for the comparative assessment of different energy systems. The key question is, where to draw the boundaries and which elements to consider for the assessment of particular energy systems. Drawing these boundaries in particular ways is frequently being used by both advocates and contraveners of particular energy conversion systems to prove or disprove their respective claims. Therefore, it is important to develop science-based criteria for delimiting the boundaries of energy conversion systems with respect to an analysis of their net energy balance.

Strongly connected to the question of the energy balance is the question of residues and wastes arising out of the application of a particular energy system. In many energy systems the energy is stored in some particular form of matter that remains in some other form after the energy has been released. A typical example are carbon-based fuel cycles, whether based on fossil or recent carbon forms, where a major operational waste product is carbon dioxide. Similarly, in nuclear energy systems spent fuel remains as operational waste. In addition, many more types of waste arise from all energy systems during their life-cycle, for instance during construction and decommissioning. Thus also so-called 'emission-free' systems, such as wind turbines, photovoltaic systems, hydroelectric and nuclear power plants generate considerable amounts of construction and decommissioning wastes. One may note that the nuclear life-cycle is not CO_2-emission free, but avoids CO_2-emissions that would arise from the alternative of using fossil fuels. All these wastes have to be managed in a way so as to minimise the environmental impact that may arise from them. Volumes and types of wastes as well as their manageability have become decisive criteria for the acceptability of particular energy systems.

Life-cycle energy costs – the case of uranium mining and milling

Methodologies

The review by SOVACOOL (2008) re-enforces the suspicion voiced by individual studies (e.g DONES, 2007) that there is a considerable divergence in the available databases and methods, leading to a wide range of overall conclusions on nuclear energy systems with respect to their energy consumption and greenhouse gas emissions. The considerable controversy over the assessment of the life-cycle energy balance of nuclear energy systems is illustrated by the rather diverging views and results by e.g. STORM VAN LEEUWEN, (2008) on one side and the World Nuclear Association (WNA, web documents on http://www.world-nuclear.org) on the other side. The controversy concerns mainly the aspects of the choice of appropriate system boundaries and the selection and availability of the respective data for individual processes and materials. Life-cycle energy balances are an element of overall sustainability analyses, not a substitute for an analysis of the value of a particular energy form. A full life-cycle analysis has to cover the flow of materials and the use of other resources as well. A life-cycle energy balance is simply a statement about the inputs, outputs and possible losses within a previously defined energy conversion system (see Figure 5).
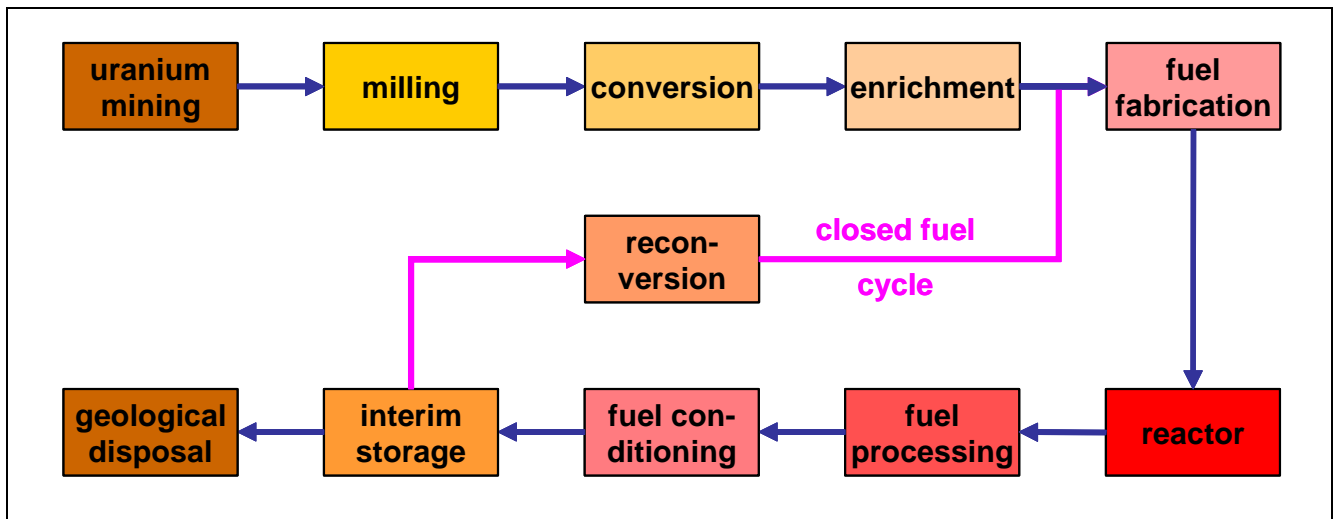

Figure 6:   The main elements of an open and closed (pink) nuclear fuel cycle.

The life-cycle of nuclear energy systems (Figure 6) in broad terms consists of those steps that provide the fuel (mining and milling) and the preparation of the fuel for use in the reactors (conversion, enrichment, fuel element fabrication), commonly called together the 'front-end'; the construction of facilities; the operation of the reactor; the storage or reprocessing of spent nuclear fuel and, finally the conditioning and deep disposal of residual high-level waste or spent-fuel, if a once-through approach is chosen, commonly called the 'back-end'. This 'back-end' may also include the decommissioning and remediation of all sites and facilities (mines, mills, fuel fabrication facilities, reactors, waste treatment plants etc.) belonging to the energy system, though some investigators treat this separate. The terms 'back-end' and 'decommissioning' does not necessarily imply that the respective activities are undertaken after all other activities have ceased. To the contrary, it is encouraged to undertake them when it is operationally expedient to do so. It is also a strong characteristic of nuclear energy systems that significant energy and materials' costs arise before and long after the useful energy production has ceased (Figure 7), though this is by no means unique to nuclear energy systems. It is likely that the life-time net energy production is much higher than in many other energy conversion system, but it still needs to be demonstrated more clearly also vis-à-vis the critics.
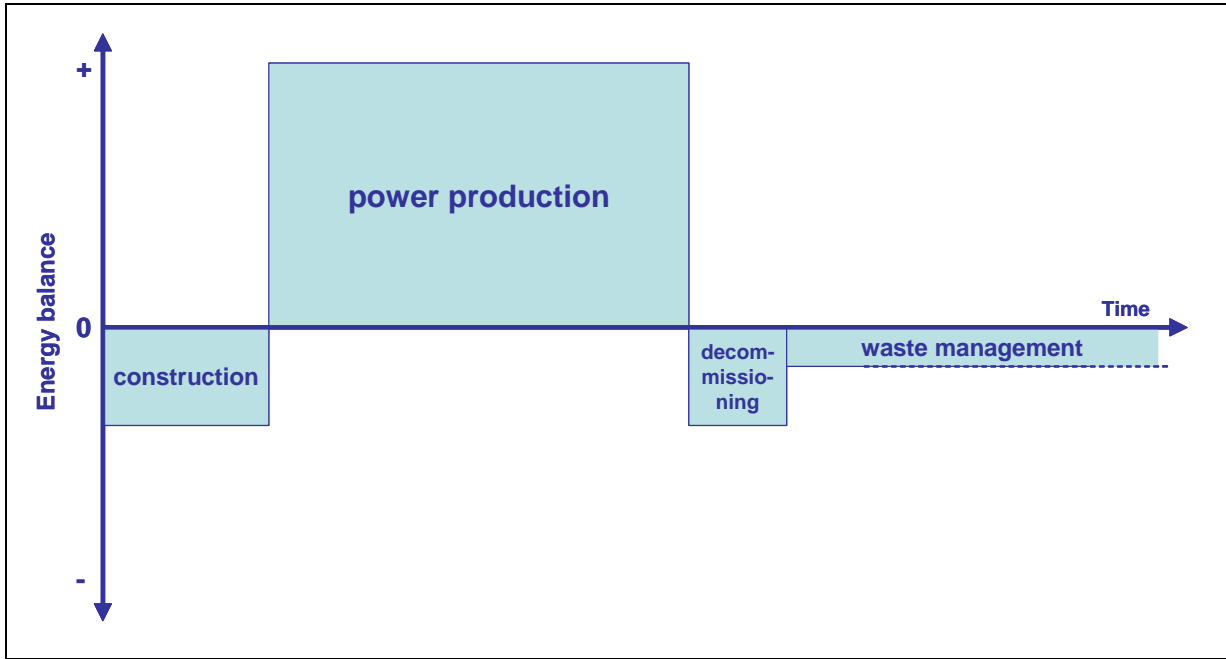
Figure 7: The time dependency of the energy balance in energy conversion systems.

While the currently available life-cycle studies vary considerably in their overall conclusions, there is still concurrence over the relative contributions of the different elements in the fuel cycle to the overall life-cycle costs (Figure 8 and 9). The major contribution to the overall emissions and hence by proxy to the energy consumption comes from the front-end of the fuel cycle irrespective of the overall size of the estimate. As more detailed analyses show (e.g. in DONES, 2007) in turn the dominant contributor is enrichment, where the technique, gas centrifuge or diffusion, is of key importance.

Though mining and milling as processes are highly integrated, they will be discussed consecutively in the following. Mining has to be preceded by a step that is commonly called exploration.

Figure 8: Relative life-cycle CO_2 emissions per kWh electrical energy produced. Mean values from the review by SOVACOOL (2008).

Figure 9: Absolute life-cycle CO_2 emissions per kWh electrical energy produced. Mean values from the review by SOVACOOL (2008).

Exploration

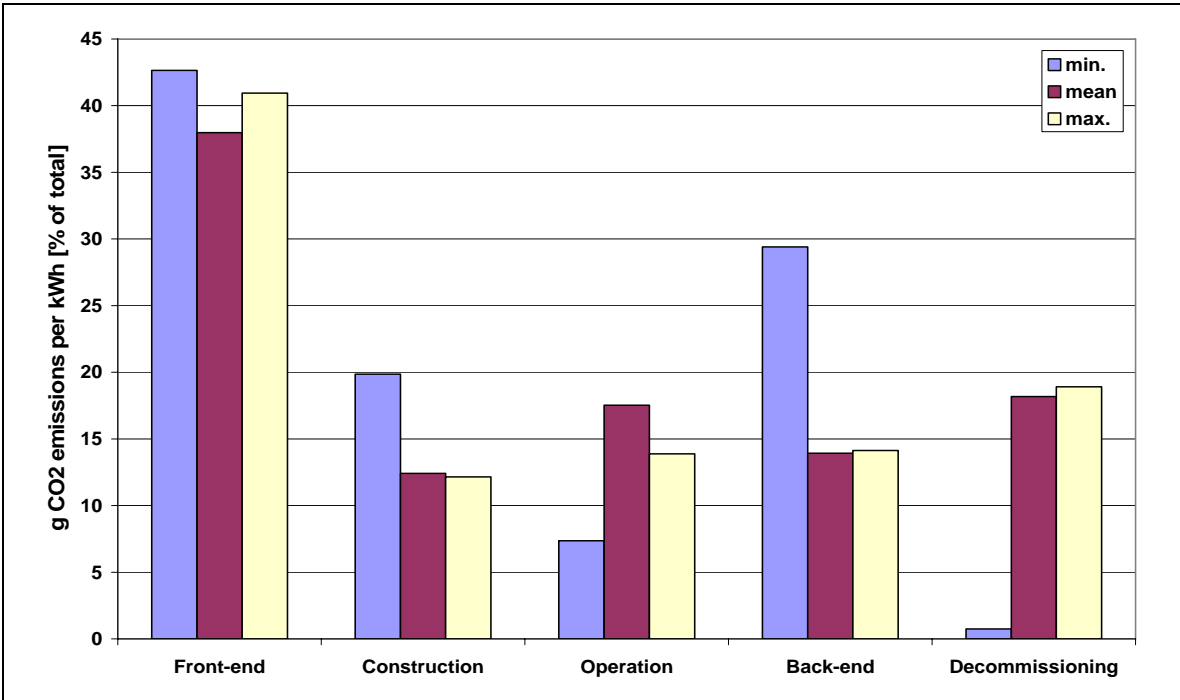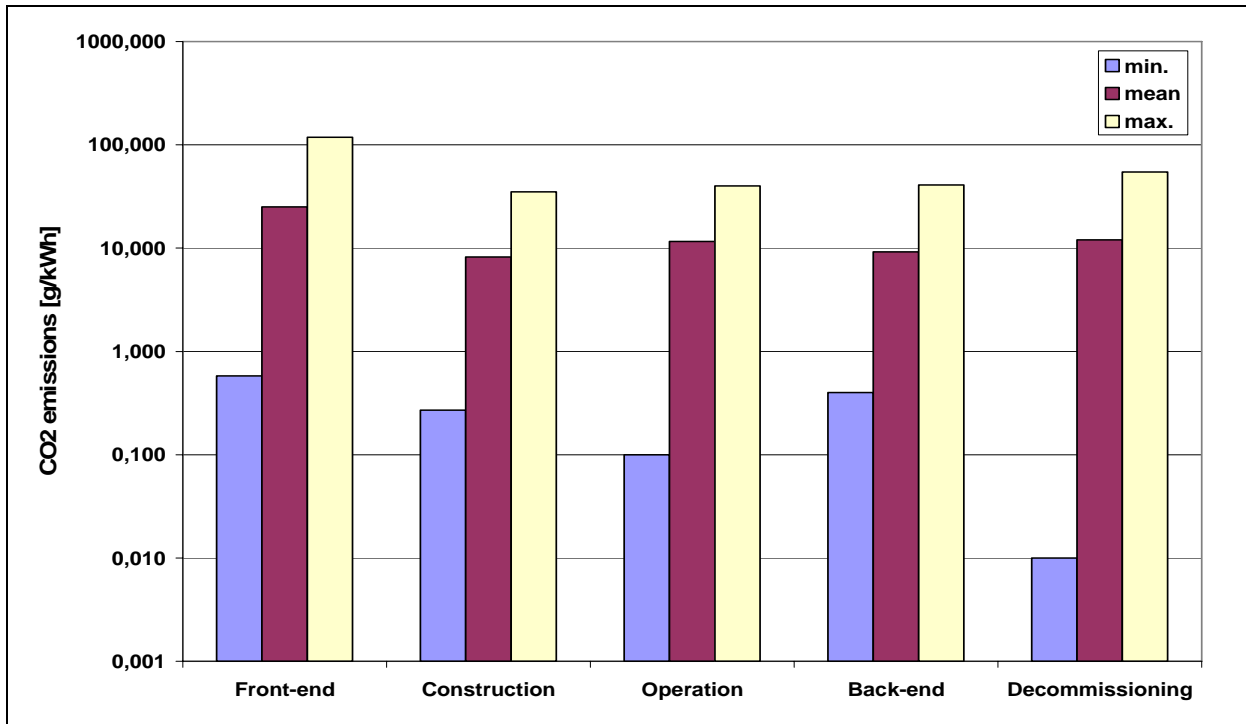Before exploitation of a mine can begin, a variety of activities occur that each have energy expenditure associated with them. These activities are generally subsumed under the term exploration. When calculating the full life-cycle (energy) costs of a nuclear energy system, as in any other system exploiting a natural resource, the difficulty of attributing the exploration costs arises. Very often there is no direct path from exploration to actual exploitation through the eventual construction of a mine. Various steps of exploration may have occurred in the course of history that lead to the accumulation of geological knowledge in a particular region that eventually leads to the targeted and specific site investigation with the view to construct a mine. However, the actual construction of a mine may be delayed for many years owing to unfavourable market conditions and other circumstances. A considerable amount of exploration also will not result in any discovery of any resources. The question here is, whether such unsuccessful exploration activities should somehow be accounted for in the life-cycle cost of actually exploited resources, and if so, in which. For practical reasons it may be very difficult to estimate the energy cost of such undertakings over a historical period. Though in the oil industry there may be statistics that estimate how many metres of exploratory bore-holes and how many kilometres of seismic profiling are needed to discover a certain amount of oil or gas. Mineral resources exploration tend to have a more one-of-a-kind character and therefore statistics appear to be scarce. Typically, energy costs, direct or embedded, of exploration consists of the energy needed to built, transport, operate and decommission equipment such as drill rigs, air-borne radiometric surveys or seismographic equipment.

Data on the energy costs of exploration are largely absent and rough estimates based on other industrial data have been used as proxies in the literature (e.g. DONES, 2007; STORM VAN LEEUWEN, 2008). **Fact-based data on the energy cost of exploration need to be collated**.

Mining

There are three principal forms of uranium mining (Figure 10): conventional underground mining, conventional open-pit mining and *in situ*-leaching (ISL). Unlike the others the latter is a form of mining that is used in practice only for uranium and copper.
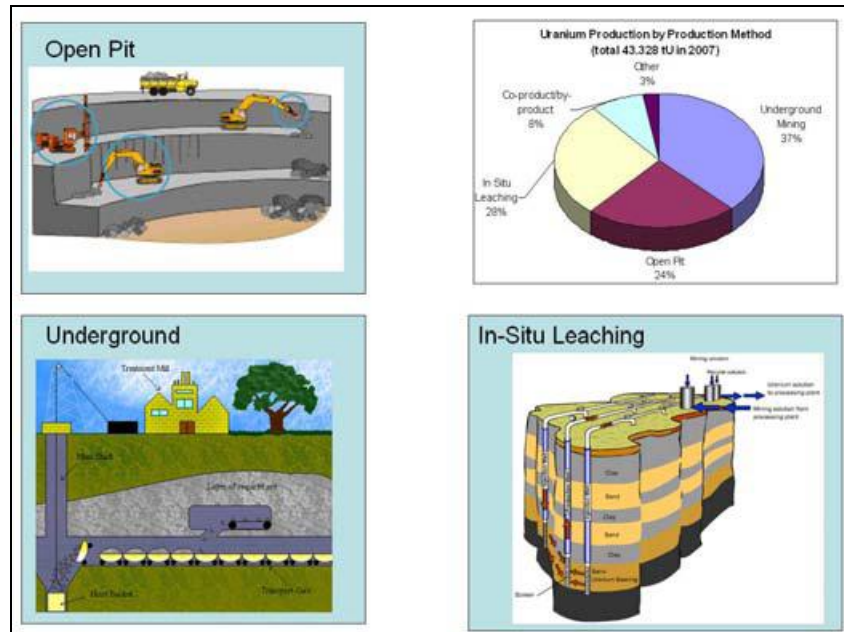

Figure 10: The three conventional types of uranium mining and their World share in production according to OECD/IAEA (2007).

A mine in itself has a life-cycle and various life-cycle (energy) costs associated with it. The energy cost of mining is predominantly associated with the removal of rocks, water and contaminated air. For an underground mine access and ventilation shafts have to be constructed together with tunnels and drifts that lead to the mineralised zone. Since mines usually are constructed below the natural water table, any inflowing water has to be removed and usually be brought to the surface for treatment and discharge. Considerable quantities of water thus have to be lifted by perhaps several hundred metres. Radon gas is a major occupational risk in an uranium mine and forceful ventilation may be required that consumes considerable amounts of energy. While radon is not so much a problem in an open-pit mine, the amount of overburden to be removed and lifted out of the pit will be considerably higher than the amount of unproductive rock removed from an underground mine. The water problem would be in principle the same as in an underground mine, though careful sealing of unproductive areas in a deep mine can reduce the amount of water to be lifted considerably.

The amount of energy stored in infrastructure depends not the least on the type of rock that needs to be excavated. In underground mines built in relatively weak rocks a large amount of lining etc. may be required for shafts, tunnels and drifts (Figure 11). The amount of this material will be much larger than what is needed for surface structures such as hoisting rigs. In the past often 'renewables' were used, meaning that props and linings were constructed from wood. Where acid mine drainage is a problem, wood may still be the material of choice. There may be also a trade-off between material and energy expenditure for different transportation systems such as conveyer belts, underground trains and road-hauling vehicles. The general development appears to go towards road-hauling equipment also in underground mines. While the operational energy expenditure of a mine can be assessed easily through the respective consumption figures for e.g. electrical energy or diesel fuel, the energy imbedded in mine infrastructure is more difficult to assess. Mass balances for raw materials or fabricated goods, such as hauling vehicles, have to be used. The use of wooden props etc. might actually positively influence the carbon balance.

Figure 11: Typical mine face, showing excavating machinery and steel liners.

A considerable amount of energy has also to be expended to break down the rock structure by drilling and blasting. For drilling typically electrical energy is converted into energy stored in compressed air, with the associated heat losses. Blasting is a process of releasing chemical energy stored in explosives. The amount of energy needed to break down the rock will depend on the rock type: vein mineralisations in granites obviously requiring more energy than roll-front deposits in sandstones. The energy required for hauling and hoisting unproductive rock and the ore to the surface is a function of the layout and depth of the mine. It can be expected that in the future higher hoisting costs will be incurred as mines will have to reach deeper down for new resources. Overall it can be expected that the energy requirements per ton of rock for hauling and hoisting will be on the same order as for other types of mines. **However, due to the high energy content of the uranium ore, the hauling and hoisting energy cost per Joule produced energy will be much lower than for fossil fuels, such as coal.** For comparison, one may consider that the energy content of the same amount of uranium and boiler coal differs by a factor of 10,000 (LEHMAN, 2008).

Figure 12: Removal of overburden in an open-cast uranium mine (Arlit, Niger) using heavy earthmoving and hauling machinery.

The unproductive rocks and below-grade ore removed from the mine (Figure 11) have to be stored or disposed of in a safe and environmentally benign way. What is considered 'below-grade' is a commercial and technical decision on a cut-off concentration below which milling is uneconomic or technically not effective with the given technology in place. In the past ores considered below grade were dumped, but may become of interest again with more effective milling technology or higher market prices. The presence of radioactive mineralisations requires safe disposal and close-out techniques (see section on 'Remediation) for such mining residues. For technical and logistic reasons a considerable amount of these materials that have been brought to the surface have to be stored or disposed of also in surface facilities. As lifting the material is energy intensive, where possible the unproductive rocks are moved within the mine and used e.g. to back-fill mined-out areas. The decision whether to backfill or not is complex and weighs against each other factors such as costs, operational requirements and mine safety. For economic reasons there is obviously a strong incentive to move as little material as possible. However, the tonnage of ore to be hauled and lifted to the surface is inversely proportional to the average ore grade. Also above-ground considerable amount of earthmoving may be required in the course of the construction of retaining dams and similar civil engineering structures. It would be futile to make generic estimates for this, as each geographical and geological situation will be different.

For conventional mining operations a comprehensive database of life-cycle energy requirements has been compiled, e.g. data in the *ecoinvent* database (ECOINVENT, n.d.). Data for ISL operations are conspicuously absent. The operational energy cost of mining depends very much on the actual location and the type of mining as briefly discussed above. For this reason it is not very instructive to provide detailed sample figures.

A database on real energy costs of mining operations per type of mining needs to be compiled. Particular emphasis needs to be given operations with low grade ores. Data from comparable base and precious metal mining operations should also be considered.

Milling

The ore will be hauled from the mine to the milling facility by conveyer belts or more likely by heavy dumpers. The ore is crushed and then ground to a very fine grain size in order to expose as much surface area as possible to the leaching agents. The subsequent process steps depend on the ore and gangue mineralogy. It may be already sufficient to mix the ground ore with water to bring a large quantity of uranium into solution (Figure 13). The resulting slurry is separated from the supernatant solution. In the following step the slurry is subject to an (acid) leaching solution. After some reaction time the acidic solution is separated from the slurry by mechanical thickeners. The uranium is recovered from the so-called 'pregnant' solution resulting from the various leaching steps by solvent extraction or ion exchange. In both cases, a re-extraction of the uranium is needed. In the final step the uranium is precipitated as ammonium- or sodiumdiuranate (yellow cake, Figure 14). A considerable amount of energy is stored in the various process chemicals. Further energy expenditure arises in the mechanical treatment such as crushing, grinding, centrifuging, filtering etc. While the latter can be measured directly by the energy consumption of the milling plant, the energy stored in process chemicals can be estimated from generic LCA sources on the respective processes (e.g. ECOINVENT, n.d.). Some mills also produce their own sulfuric acid from the raw materials, which saves on hauling cost. Such processes need to be either assessed individually or can be subsumed in the overall energy consumption of the milling plant.

The milling residues, the so-called tailings, usually are pumped to pond-like disposal facilities (Figure 15; e.g. IAEA, 2004b). Some conditioning to improve flow or settling behaviour may be needed as well as the neutralisation of residual acids from the leaching. This neutralisation is effected by the addition of ground carbonate rock. The energy required to pump the material to the tailings pond can

Figure 13: Heap leaching of low-grade ore (San Rafael, Argentina).

Figure 14: Yellow cake, the final product of milling (Arlit, Niger).

Figure 15: Tailings pond at Arlit, Niger.

be measured at the plant. To this the life-cycle energy cost of the neutralising agents, which would include their mining, their conditioning and their transport to the facility, need to be added. There is also a considerable amount of energy stored in the retaining structures that need to be constructed for

the tailings ponds, such as dykes (e.g. IAEA, 2004b). Most often these structures are built from local materials, but specialty materials, such as plastic foils as liners, may need to be brought in. The life-cycle energy stored in these materials must be included into the balance. In a more recent development in Canada, tailings are pumped into specially constructed underground disposal facilities (**REF ?**). The energy cost for the construction of these must be assessed.

To date no substantiated database on all these energy costs exists. The compilations in e.g. the *ecoinvent* database (DONES, 2007), for the lack of more specific data, are largely based on assumptions and old investigations, some of which date back to the 1970s. **In order to confirm these assumptions data should be collected from the respective producers.**

In situ Leaching (ISL) operations

ISL operations are treated separately here as they range conceptually somewhere between mining and milling (IAEA, 2004a). In ISL a set of wells is drilled down around the mineralised zone into which the leaching solution will be injected. A second set of wells is drilled into the mineralisation from which the 'pregnant' solution will be pumped. A third set of wells some distance away ensures an overall inward hydraulic gradient into the system so that no leaching fluids can escape. The solvent is usually acidic, namely sulfuric acid, but in carbonate rocks alkaline solvents have to be used. More recently enhancing recovery efficiency by biomining techniques is being explored. Thus 10-15% of the world copper production comes from bioleaching of spoil heaps (e.g. SCHIPPERS, 2009). For a discussion of the techniques in a remediation context see e.g. IAEA (2006a,b), but a review of these interesting aspects is beyond the scope of this report.

The major energy expenditure occurs during the drilling of the various injection, pumping and hydraulic protection wells that make up the ISL system and during the forced circulation of the leaching liquid. A considerable amount of energy would also be stored in the leaching chemicals, either sulfuric acid or hydrogen carbonate solutions and neutralisation agents. Except for the well casings, pumps and solution distribution network, not much energy would be stored in the infrastructure.

A mill in conjunction with an ISL operation does not require equipment such as crushers and ball-mills. The leaching fluids are already introduced at the mining stage, rather than at the milling stage. The mill thus largely comprises the steps from the solvent extraction on. Due to the absence of primary slurries, the only solids arising are those from neutralisation and precipitation steps.

Not that many ISL operations are ongoing currently, but operational data on energy requirements could also be obtained on ISL data from copper mines for comparison.

In spite of the advantage of not producing large quantities of mining and milling residues, ISL operations remain controversial. The main problem is seen with the long-term impact on the aquifers in which the mineralisations are located. To a large extent the public view was formed by the rather poorly controlled operations in the former GDR and in the Czech Republic. These were, however, not ISL operations in the strict sense of the word. They were a combination of underground mining and underground block leaching. While complete removal and/or neutralisation of the leaching fluids at the end of the operation may be difficult, it should be noted that in most cases due to high salinities and other problematic dissolved constituents the aquifers in question would not have been suitable as a resource for drinking water anyway. It is important, however, to prevent leakage of contaminated fluids into other aquifers through short-circuiting via boreholes that have been inadequately sealed. More recently advances in biotechnology with extremophile micro-organisms that thrive in low-pH environments are being explored for the remediation of sites with high concentrations of acidity (IAEA, 2006a,b).

Very little specific information on energy requirements for the remediation of ISL appears to exist. In the past energy requirements from similar technical operations were used, e.g. in DONES (2007). It should be, however, possible to obtain data from operators.

As ISL appears to gain market share, realistic life-cycle energy balance should be established, perhaps also with data from other solution mining industries.

Remediation of mining and milling facilities

It has been the practice for centuries to simply walk away from exhausted mines and leave behind infrastructure for which no further use could be found. Similarly, disposal facilities for mining and milling residues were simply abandoned. Such practice is not acceptable anymore (Figure 15). National and international legislation now requires the orderly decommissioning of infrastructure and closure of residues management facilities (IAEA, 2002a; 2006d). This applies in principle not only to uranium mining, but to all kinds of mining, whether for fossil fuel, base and precious metals, or other geological materials, such as limestone, clay, gravel etc.

Figure 15: The progress of remediation over a 20 year period at one of the Wismut uranium mining sites gives an indication of the amount of energy expenditure required.

Estimates of energy requirements will be determined by the local circumstances and the previous disposal practices. Energy requirements can be minimised by practices that keep final disposal requirements in mind. The energy requirements will also be determined by the chosen and permissible remediation option. Typical long-term remediation options are discussed in IAEA (2004b,2006c). These options are comparable to those in other types of mining, but taking into account the specific long-term radiation protection requirements. The long-term management of closed tailings ponds presents a well-recognised problem (FALCK, 2008) that has sometimes been used to exaggerate the energy cost of uranium production (e.g. STORM VAN LEEUWEN & SMITH, 2008). Industry estimates of monetary cost of remediation are around 10 US$/kg uranium (LERSOW & MÄRTEN, 2008). Re-emplacement of tailings into underground mines will in general not be feasible for technical and mine safety reasons. IAEA (2004b,2006c) present a range of management options that do not require very energy-expensive stabilisation techniques involving the use of large amounts of additional materials as

stipulated in Storm van Leeuwen & Smith (2008). In the case of open-pit mining often the tailings are already re-emplaced into the mined-out pits.

One should also be careful not confuse the sometime immense remediation costs for historical legacies, which seem to dominate the existing literature, with the comparatively much lower costs for the orderly close-out of new operations that are also almost always guaranteed by bonds and similar financial instruments and would not receive operating licenses without these (IAEA, 2002b).

The requirement for long-term stewardship (IAEA, 2006c) entails also long-term, trans-generational energy costs for maintenance etc. This problem is being actively addressed in the context of uranium mining and milling residues, but seems to go largely unrecognised in the context of other long-lived waste management facilities, such as hazardous waste landfills. It is mainly an ethical question whether and how to internalise these costs. In any case, it is clear that future generations will benefit from the accumulated use of the energy in the first place, as we do benefit from the energy expenditures of previous generations.

To date, the subject of total energy requirements and hence the energy-related emissions of close-out and remediation of uranium mining and milling facilities has not been addressed explicitly. No hard data have been collated yet from actual cases and all calculations in LCAs are based on assumptions (e.g. Dones, 2007). **Hence, data on completed and ongoing uranium mine/mill remediation projects e.g. from France, the Czech Republic, Germany, or Portugal should be collated. These European data could be compared with data from the Australia, Canada and USA, if available.**

The focus in the energy debate is on GHG emissions, however, disposal sites for residues from energy conversion systems may have other emissions, including polycyclic aromatic hydrocarbons (PAH), volatile organic carbons (VOC), heavy metals and natural radionuclides (NORM), both in dissolved form and as gases (for the NORM-problem see e.g. IAEA, 2003). While the awareness of such emissions has slowly risen in the western world over the past decades, this is by no means so in the developing world, where fuel and other raw materials imports for Europe may originate from. Driven mainly by radiation protection consideration, but not only so, the life-time emissions from uranium mining and milling residues are being regularly assessed during the licensing of the respective facilities. Extensive R&D and design studies have been undertaken to minimise such emissions, including the radioactive gas radon and certain aqueous radionuclide species. It would be beyond the scope of this report to discuss 'life-time' emissions from such facilities and the reader is referred to IAEA (2006c) for a comprehensive discussion of the subject.

Meeting the energy requirements of uranium mining and milling

Since much of the (uranium) mining and milling has moved to locations outside Europe and to often remote locations, the efficient provision of the energy required becomes a crucial variable in the process to assure sustainability. Typically, such operations are not and cannot be connected to large-scale electricity grids. Hence, they provide for their energy requirements through dedicated fossil fuel-fired power plants. This fuel has to be transported to these locations over long-distances too, which further increases energy requirements and GHG emissions. The fuel of choice is mostly oil (e.g. diesel) for both mobile and stationary machinery including power plants, but there are examples, where other fossil fuels are used. Thus the Number 4 uranium producer in the world, the mines and the mill in Arlit in northern Niger are powered by a coal-fired powered station that uses locally mined hard coal.

In order to reduce the CO_2-intensity of uranium mining and milling, which is a significant contributor to the GHG-emissions of nuclear energy systems, one could explore the increased used of renewables in this sector. The location of the sites at often remote locations would facilitate the use of low-density energy conversion systems such as solar radiation capturing systems. One could imagine that in countries such as Niger or Australia solar systems would have a considerable potential to power the

mining and milling plants. In South Australia's Four Mile ISL facility, to be opened in 2010, a geothermal system will provide the main external energy input (http://www.miningweekly.com/article/new-australian-uranium-mine-to-be-powered-by-renewable-energy-source-2009-05-04, accessed 25/05/09).

Box: The uranium mines in Arlit (Niger) would make an interesting case study for assessing the energy requirements of mining/milling. Arlit has limited connections with the outside world and limited cross-links with other industrial activities. Power for the mining and milling operation and the town supporting the operations is generated in a coal-fired power plant (SONICHAR) some distance away. Apart from the largely untapped natural solar radiation, the only other direct energy input appears to be fuel for the vehicles. It should be possible to get data from AREVA and SONICHAR

http://niger.areva.com/niger_home/liblocal/docs/AREVA%20au%20Niger%20janvier%2009.pdf

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Possible scenarios, technical feasibilities and logistics for low-carbon energy supplies to uranium mines and mills could be explored together with the relevant producers.

Security of supply - uranium resources

What is a resource ?

Another crucial point in the discussion over the public acceptability of nuclear energy systems is the question, whether there will be enough fissile elements to sustain or even expand a nuclear power programme and whether we can 'afford' in terms of energy consumption and environmental impact to tap into this natural resource. The question, whether the uranium (and thorium) would suffice to sustain useful nuclear energy programmes has been discussed repeatedly in the recent scientific and technical literature, e.g. PRESTON & BARUYA (2006) or MACFARLANE & MILLER (2007). The development of the demand side over the next half century has been tried to capture by developing various scenarios, but must remain rather speculative (OEDC-NEA/IAEA, 2001c,2008).

Resources limitations as a potential societal phenomenon had first been highlighted by a much cited Club of Rome pamphlet (MEADOWS, 1972,1974), but actually has not had the predicted effect within the predicted time-frame. The reasons include resource substitution and changing views of acceptable price levels due to a changing overall socio-economic situation. Today's relative and absolute prices of some commodities would have been unthinkable 30 or 40 years ago. The discussion in the following will focus on uranium, but in principle would also be applicable to thorium.

Arguably the most authoritative source on uranium resources is the so-called 'Red Book', a periodical joint effort of a large group of international experts under the joint aegis of the OECD-Nuclear Energy Agency and the International Atomic Energy Agency and named after its red cover. The latest edition dates from 2008 (OEDC-NEA/IAEA, 2008).

As is the case for all other natural resources, there is a considerable difference between what is the global inventory in terms of materials and what is recoverable for human use and consumption. Depending on the organisation concerned and the context there exist varying definitions and terminology for resources of different levels of availability. Common to all definitions is that they are made on an economic basis, usually a current or assumed cost of recovery. While they make sense in a purely short to medium term economic context, such definitions are not helpful in assessing long-term resources availabilities, for instance for a strategic assessment of the viability of nuclear energy systems. The cost of recovery is a factor of the available recovery technique and the cost of its

deployment. The amount recoverable depends on the overall efficiency and effectiveness of mining and milling techniques.

There are averaging estimates for the global abundance of uranium, which is 2.8 ppm in the Earth's crust. For comparison, the average crustal abundances of gold and silver are 0.004 and 0.06 ppm respectively (WEDEPOHL, 1969). So uranium is by no means a particularly rare element. The crucial problem is that only a fraction of the total inventory is actually known in terms of its location and extent. For arguments sake, assuming that a layer of 1 km depth is mineable, this results, with a surface of the solid earth = 1.469×10^{14} km^2 and a rock density of 2.7 g/cm^3 in a total mass of 3.9×10^{23} t. These number would result in a global inventory of 1.1×10^{18} t uranium, 2.4×10^{16} t silver, and 1.6×10^{15} t gold respectively. It is interesting to compare these number with retrospective estimates of the total amounts of each element mined so far in human history. Thus it is estimated that 140,000 t of gold have been mined globally over the history of mankind (ZURBUCHEN, 2006), which is only about 0,0059 ppb of the global inventory down to 1000 m depth. The remaining reserve base is estimated to be about 100,000 t (USGS, 2009). For silver the figures are 1,325,630 t mined (BUTTERMAN & HILLIARD, 2004; ZURBUCHEN, 2006) during human history, which is 0,84 ppb of the inventory to 1000 m depth, with a remaining reserve base of 570,000 t. (USGS, 2009). Conversely the cumulative uranium production since 1945 has amounted to about 2.2×10^6 t (PRICE et al., 2006), which is about 0,002 ppb of the global inventory to 1000 m depth. The estimated recoverable resources (at US\$130/kg U) are in the order of 5.5×10^6 t U (OEDC-NEA/IAEA, 2008).

In this context it is also interesting to note that while most of all the uranium ever mined can be still accounted for and only some 12-15% of all gold ever mined has been lost (ZURBUCHEN, 2006), the use of silver is or was to a significant extent dispersive, e.g. in photographic emulsions.

It is also interesting to compare the prices per kg for the three commodities uranium, gold and silver, which were in March 2009 around US\$15 (http://www.uranium.info), US\$29700 (www.goldprice.org) and US\$410 (www.silverprice.org) respectively. In other words, we are currently prepared to pay 27 times more for a commodity that is produced at about half the rate (20,900 t silver in 2008; USGS, 2009) of that of uranium (42,000 t in 2007; WNA, http://www.world-nuclear.org/info/uprod.html) and nearly 2000 times more for a commodity that is produced at 5.5% the rate. It is clear that the majority of the global inventories of uranium, gold and silver are too finely dispersed in order to be accessible to any form of mining. The point is, however, that relatively speaking a disproportionately high effort, as expressed in terms of price, is spent on recovering a resource that is by a factor 100 or even 1000 less frequent. In other words, if we are prepared to spend comparable amounts of money on the exploration and recovery of uranium as we do on silver, the available resource is likely to increase by orders of magnitude. There is also a certain geochemical logic in this, as some of the primary mineralisations for all three of these elements are similar. In fact, one of the currently biggest uranium producer (Olympic Dam in Australia) is a co-producer of gold and uranium. In the past a doubling of resources for every two decades due to prospecting and exploration was observed (LEERSOW & MÄTTIG, 2008).

To date 0.005 ppb of the global inventory of uranium, 0.0042 ppb of that of gold and 0.35 ppb of that of silver have been identified as economic resource. If the same amount of effort would be spent and if the price of uranium could be in the order of that of silver today (i.e. US\$400/kg), the economic resources of uranium should be extended by a factor of 100 at least. DEFFEYES and MACGREGOR (1980) already noted the parallel between uranium and silver in terms of crustal abundance, a certain similarity of price development until that time and the fact that the then leanest ores mined were enriched about 2000 times over the average crustal abundance.

In this context it is worth noting that very little money (compared to general energy demands) has been invested into uranium prospecting from the early 1980s to the beginning of the 21st century. Overall, much less money per energy unit has ever been spent on prospecting for uranium than on prospecting

for oil or on precious metals. Most of the known mineralisations have been known for decades and were discovered during the early years of the nuclear history. So with adequate spending on prospecting, it is likely that more mineralisations (and not only the diffuse ones, such as phosphates or seawater) are being discovered.

Distribution of concentrations and mineralogical forms of uranium

In a well-known graph (Figure 16) the estimates of global abundances are related the to average uranium abundances in different rock types. It was originally drawn up by DEFFEYES & MACGREGOR (1980) and LEHMANN (2008) added the high-grade deposits discovered in Canada later. There is an apparently gap in the bell-shaped distribution curve for recognised occurrences with abundances from 0.001 to 0.1 ppm. While some authors (e.g. STORM VAN LEEUWEN & SMITH, 2008) used this apparent gap to argue against the long-term prospects of nuclear energy, its causes need to be further investigated. However, it is not very likely that rocks with abundances below the crustal averages would ever be mined.
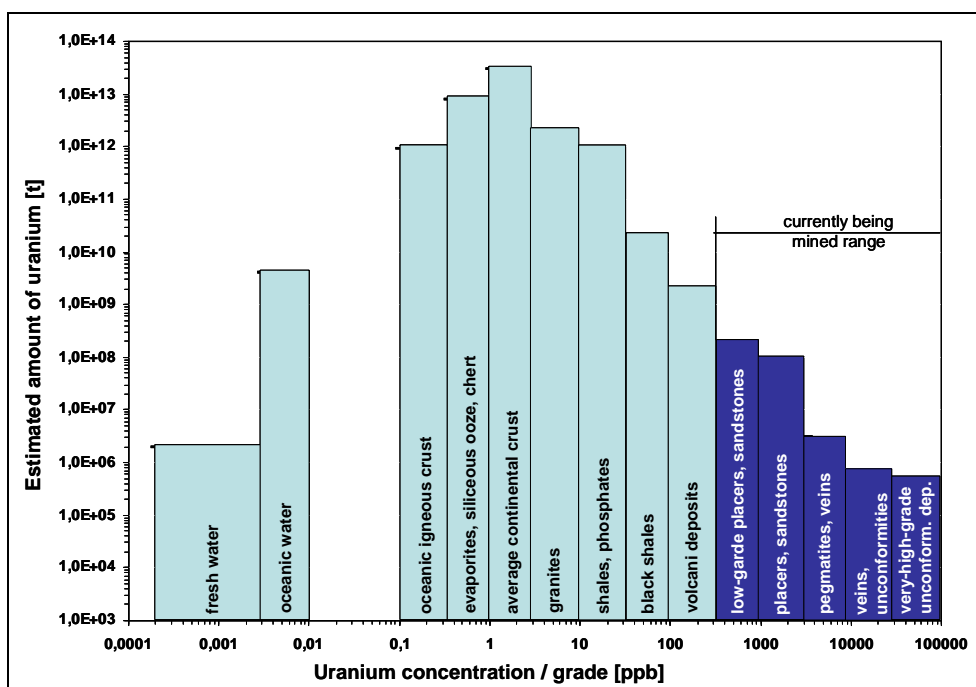

Figure 16: Distribution of uranium in classes of abundance (after DEFFEYES and MACGREGOR, 1980, with modifications by LEHMANN, 2008).
Note that areas of columns under the distribution are not cumulative !

Not only the rock concentrations are a crucial factor, but also the mineralogical form in which the uranium occurs. Uranium has two major oxidation states, the +IV and the +VI state. A third, +V state is still debated with respect to its geochemical relevance (GUILLAUMONT et al., 2003). In consequence, the aqueous and solid state chemistry of uranium is rather complex. In the oxidised +VI state uranium does not occur as an individual cation, but as the oxy-anion UO_2^{2+}. This uranyl ion can substitute for a whole range of divalent oxy-anions, such as sulfates, arsenates, vanadates, molybdates etc. Hence, uranium can occur as an accessory in many different minerals. These compounds typically have low solubilities, which means that a relatively high amount of energy would be needed to transfer the uranium into the liquid phase. There are also numerous uranium silicate minerals known that might occur finely dispersed in a matrix of siliceous rocks. Comprehensive reviews of uranium ore formation and occurrences are provided, for instance, by DAHLKAMP (1993) and by PLANT et al. (1999).

The amount of energy needed to bring some of these uranium minerals into solution for further processing as nuclear fuel would be probably prohibitive from an overall energy balance point of view. **For further assessment, it would be helpful to have a database available that compares the energies required to breakdown and dissolve the uranium ore from different rock types and mineralisations.**

Based on these considerations and considering the distribution in Figure 15, one can conclude that at least half of the global inventory would be energetically prohibitively expensive to mine and mill by any standards (see discussion in the following section). The oceanic crust in addition would be very difficult access for mining at any scale.

One could question the validity of drawing a curve as the one in Figure 15, as it combines different geological compartments, such as the solid earth and the surface waters. Further combines this graph two fundamentally different redistribution processes for uranium, namely igneous processes and exogenous erosion and sedimentation processes. The very rich ores at the upper end of the distribution are mainly the result of igneous and hydrothermal processes. In turn, the low concentrations in evaporites reflect the concentrations of the sea- or freshwaters from which they have been derived. For instance, one kg of seawater contains about 35 g of salt and about 1×10^{-9} g of uranium; after evaporation, one kg of salt contains just under 3×10^{-8} g of uranium, which indicates an additional enrichment process as measured data are one order of magnitude higher. This reasoning about different redistribution mechanisms might explain the apparent gap in the distribution curve that in fact might be a bi- or multimodal distribution. The gap may also disappear, if the averaging would be undertaken over smaller units than e.g. average 'igneous oceanic crust'. One could decompose these averages by compiling measured uranium concentrations in as many rocks as possible. However, for the energetic reasons alluded to above and discussed in more detail in the following, it may not actually further the objective of discovering accessible uranium resources.

Resource estimates vs. energy requirements and extraction efficiency

The amount of available uranium resources are commonly defined on an economic basis, or more precisely on the (currently) acceptable market price of uranium - see OECD-NEA/IAEA, 2008, for a definition of the different resources categories. A categorisation relative to current market prices is understandable from a producers and consumers point of view, but rather inadequate from a long-term strategic point of view. There is also little economic incentive for mining companies to convert resources into reserves years ahead of a possible demand. Therefore, the categorisation in OECD-NEA/IAEA (2008) is likely to be rather conservative. In order to arrive at a categorisation that is more useful for very long-term strategic planning and independent of market situations, it may be more adequate to use as a basis the energy required to convert the uranium resource into yellow cake, the marketable form of uranium. While production techniques are constantly being improved in order to reduce energy and other costs, there are limitations to this that are dictated by geology and thermodynamics.

Ore formation is a process controlled by thermodynamics in either aqueous solution or a rock-melt environment. In either case the ore minerals are a (meta-)stable form of uranium for a given environment. Hence work has to be invested to change this thermodynamic state and bring the uranium back into solution – all the reactions taking place during the milling process are endothermic. Some uranium minerals are more readily dissolved than others. Thus typically uranium minerals in sedimentary formations or where the uranium forms secondary impregnations in other types of rocks require less energy than primary uranium minerals, e.g. silicates in igneous rocks such as granites. Uranium minerals in igneous rocks are typically more refractory than those in sedimentary rocks. In addition, the shear and compressive strength of igneous rocks tends to be higher than that of sedimentary rocks. In addition and due to the rock-forming processes, igneous rocks do not have open

pores and, hence, internal surface areas are much smaller than those of sedimentary rocks. These properties mean that more mechanical energy is required to break down the rocks to grain-sizes that allow ready access to the leaching agents.

To date only a limited dataset on the energy requirements for uranium milling exists. **It would be useful to have detailed energy breakdowns for the different steps in the milling process such as crushing, ball milling, leaching, solvent extraction, thickening, drying.** These would allow better quantitative assessments of the viability of mining lower ore grades and thus to extrapolate the assessment by MUDD & DIESENDORF (2008) to lower ore grades. Process-specific data in the *ecoinvent* database (ECOINVENT, n.d.) for similar processes from other industries could be corroborated in this way. **Extraction yields and efficiencies should also be compared with those from similar industries**.

It is very attractive that the uranium in seawater is already available in a readily dissolved form. No energy is required to bring it into solution, but its entropy is very high, meaning that a considerable amount of energy has to be invested to concentrate the uranium into useful quantities (e.g. SEKO et al., 2003). **It may be worthwhile to investigate processes in which seawater is concentrated and desalinated for different purposes, whether the resulting liquid and solid residues could be utilised as by-product sources for uranium** (e.g. SODAYE *et al.*, 2009). It is notable that the majority of the references cited in this work data back to the 1980s, 1970s and even 1960s. Extraction procedures would need to be developed that are sufficiently specific for uranium and do not result in difficult to manage wastes. To date various processes based on ion exchange or adsorption (SEKO et al., 2003, TAMADA et al., 2006, SODAYE *et al.*, 2009) and on processes akin to bioremediation are being investigated for instance in Japan. In the latter case seaweeds with a high affinity for uranium are being cultivated that at the same time form a carbon sink and biofuel (http://www.wise-uranium.org/upasi.html#JP, accessed 25.05.09). A calculation on the 'back of an envelope' reported by MACFARLANE & MILLER (2007) indicates that about 5% of the demand in an average nuclear growth scenario could be met. It could be indeed interesting for countries such as Japan that do not have land-base uranium resources and suitable conditions for this kind of marine 'bio-mining'.

Under the heading of 'unconventional' resources the recovery of uranium as by-product from other extractive processes or from the residues of such processes is often cited. The most often cited examples are the phosphorous ores mined for the production of fertilisers and the various residues from coal mining and burning as fuel in e.g. power plants. Due to the fact that uranium and other heavy metal phosphates have very low solubilities, phosphate ores are often enriched in the respective elements. These and particularly the radioactive ones (i.e. Naturally Occurring Radioactive Materials, NORM) can cause various problems during processing, waste management and the application of the fertiliser (e.g. IAEA, 2003; FALCK & WYMER, 2005). Following *inter alia* studies initiated by the European Commission (e.g. BAETSLÉ, 1991), importers of phosphate ore have become more selective in their use of sources, effectively excluding certain ore producer countries from the European market (see IAEA, 2003, for more information). It may be interesting to explore possible synergies between obtaining uranium as by-product from fertiliser production and enlarging the resource base for fertilisers, while at the same time making (technical) advances in the management of phosphogypsum residues and products that contain NORM (e.g. BUNUS et al. in IAEA, 2001b). Although their comments are not entirely impartial, the warning by STORM VAN LEEUWEN & SMITH (2008) should be heeded that there is an inherent danger that uranium becomes the main driver for mining phosphate, thus undermining possibly our ability to provide the fertiliser to sustain an ever increasing world population. One should note, however, that this warning is only relevant, if the residues are discharged into the sea, as it is the current practice in some countries. If the residues were stockpiled, the phosphorous would not be lost.

The burning of certain types of coal results in large volumes of NORM-containing fly-ashes and, if scrubbers are installed, in NORM-containing gypsum from the flue-gas desulfurication (e.g. IAEA, 2003). While it is desirable from a management point of view that these wastes contain the NORM in a as inert as possible form, recovery of uranium from them may have the opposite objective. Much of the radionuclide content is, however, made up of ^{226}Ra and ^{210}Po. Typically, NORM in fly-ash are enclosed in a glassy matrix, but the small grain size results in a large specific surface area that would make the material more accessible to dissolution. There are already commercial companies exploring such potential resources (e.g. http://www.spartonres.ca/, accessed 25.05.09). **It may be worthwhile to undertake a world-wide survey of the uranium content in such residues, of its mineralogical form and of the respective energetic requirements to utilise these resources**. There is already a considerable database in the literature on specific radionuclide concentrations, but no assessment whether the respective residues would be amenable to reprocessing. In the long-term, one may also want to look into the combustion processes in order to improve by-product recovery efficiency.

It can be envisaged that at a point when richer ores become exhausted, mining and milling companies may turn to reworking of older process residues and of material considered to be sub-grade in earlier times. A phenomenon not unknown in the precious and rare metal industries. **Again it may be worthwhile to assess on a world-wide basis the potential of this resource.**

The reported quantity of resources may be somewhat misleading for political decision makers, as total quantities and not recoverable quantities are reported. In each step, from mining to the packaged yellow cake the recovery efficiency that is less than 100%. For technical and thermodynamic reasons there will be process losses at each step. Depending on the type of mineralisation and on the mining technique it is not possible to recover all of the ore. Nearly full recovery would only be possible with conventional open-pit or underground mining, if the zone of mineralization has very well-defined boundaries. The recovery rate of in situ leaching (ISL) mining depends on the geological parameters, such as the permeability of the rock and the ore mineralogy. Rates can be as high as 95%, but could also be as low as 60% (IAEA, 2001a, 2004a). Higher rates are usually associated with acidic leaching systems, while alkaline leaching systems tend to have lower recovery rates and require longer residence times.

Ore processing is a reasonably well controllable industrial process. Its main variable, the ore grade as it comes out of the mine is adjusted by mixing ores of different grade that are stockpiled for this purpose; this allows to optimise the processes in the mill. The milling process typically involves the steps of crushing, grinding, (acidic) leaching, solvent extraction, precipitation, thickening and drying, with 'yellow cake', i.e. sodium- or ammoniumdiuranate as the product. Some of these steps may have small losses, e.g. in the form of dust. For thermodynamic reasons, the efficiency of the wet-chemical steps cannot be 100%, but is only in the order of 95%. The resulting losses are multiplicative, so that the three consecutive steps of leaching, extraction and precipitation with 95% efficiency would result in an overall process efficiency of only 85%. With decreasing ore grade the extraction efficiency drops. As process efficiencies have been improved over time, it could be worthwhile to re-process old tailings.
One can thus roughly estimate that less than 80% of the original uranium content of the ore body will actually be available for fuel fabrication. **It would be worthwhile to compile process efficiency data vis-à-vis a more realistic assessment of the net resources available.**

Reporting of uranium resources

Until the end of the Cold War uranium was not only a economic strategic, but above all also a military strategic resource. Therefore, a free market existed only with limitations and the whole industry was clouded in secrecy. Although in many countries a free market economy for uranium has developed since, there remains still the aspect of a strategic national resource that may result in non-market led behaviour (PRESTON & BARUYA, 2006). The 'Red Book' (OECD-NEA/IAEA, 2008) is compiled by a

large group of national experts under the aegis of a joint NEA and IAEA secretariat. The data reported are those the 'official' ones reported by the national representatives and there is very little scope for independent assessment. It is not known, whether there may be still political constraints on reporting in some countries. Similarly, there could be economic interests in reporting low figures by mining companies with the view, for instance, to keep prices high. Conversely, mining companies might report optimistic figures in order to attract investors. It is very difficult to verify or let alone validate the reported resources.

It has been noted variously that there can be a time lag of decades between the discovery of resource in the first place and its subsequent assessment and exploitation. It was noted with the idea to imply that there may develop a supply bottleneck, if demand should increase. While this observation certainly is historically true, considering that the most recent discoveries fell into a time of reduced demand, one may hold against that a resource is only being developed, if there is an economic demand for it. No company would invest considerable amounts of money into the development of a mine, if there was no expectation of a return within a reasonable time horizon – typically within a few years.

From a global energy supply sustainability point of view neither commercial nor national strategic considerations nor time considerations are really relevant. For an independent assessment of the sustainability of the nuclear fission option for energy conversion the only question relevant is: how much in terms of resource in which energy cost category is available ?

Data sources and their reliability

When discussing the viability and sustainability of nuclear energy conversion systems, much of the debate pro and contra circles around the reliability and acceptance of the databases used for the assessments as discussed above for the reporting of resources. Process and other data coming out of the industry itself or out of pro and contra lobbying organisations, should both be regarded with some reservation. In assessing the quality and reliability of the data, it is helpful to reflect on the following questions:

— who owns the data?
— who generated the data?
— who collated the data?
— for what purpose were the data generated/collated originally?
— are the data updated regularly?
— who determines which data are generated/collated?

In the context of developing and marketing proprietary, computer-supported tools for LCAs comprehensive database have been assembled. Through massive LCA undertakings, such as *ecoinvent* (ECOINVENT, n.d.) or *GEMIS* (http://www.oeko.de/service/gemis/en/index.htm), comprehensive materials and energy consumption databases for a wide variety of industrial and other processes have been collated. None of these are freely available, however. Access has to be purchased together with a license for the respective LCA code. There are some publications that describe the sources and selection criteria for the data in the *ecoinvent* database (e.g. DONES, 2007, for the nuclear systems), though these are only available to the license holders. There does not appear to be a similar publications describing the GEMIS data. Therefore, an independent assessment and public scrutiny of the data with respect to quality, underlying conceptual model and selection criteria is not possible based on open literature. While some of the databases may comply with formal quality management criteria as set down in the ISO9000 series, this does not prevent the arbitrary selection or omission of data as discussed above.

For the more industrial and process industry-like aspects of the nuclear energy systems data have been published, though a considerable quantity of them are several decades old already, as becomes quickly evident by browsing the reference lists in both, STORM VAN LEEUWEN & SMITH (2008) and DONES (2007). A considerable amount of guess work and assumptions, however, go into the assessments of front- and back-end of the fuel cycle, as DONES *et al.* (2005) and DONES (2007) point out.

In his recent review paper SOVACOOL (2008) assessed the available life-cycle analyses of nuclear systems (or parts thereof) by similar criteria. While some of the criteria he used, such as age, language of report, public domain vs. proprietary may largely reflect the author's particular position, the criterion whether the authors of the studies have revealed or are willing to reveal their sources is much more serious. Excluding from a sample of 103 the 40 studies that are more than 10 years old may seriously curtail the assessment of an industry that has, for instance, seen very little new power plant construction over the past 20 years. Similarly, language can be a barrier, but a barrier that can be overcome easily in an international context. Compiling material flow databases is a very labour-intensive effort and therefore it is not surprising that one has to buy-in into some of the more serious undertakings, such as ECOINVENT (n.d.). One should also not forget that most of their contents was compiled for industries' use and therefore has a significant commercial value. Nevertheless, one would strongly agree with SOVACOOL (2008) that the credibility of life-cycle studies in the nuclear industry very much depends on the public accessibility (and scrutiny) of the underlying data. **It is interesting to note that only a very small number of the reports finally selected by SOVACOOL (2008) actually cover the fuel cycle up to the production of yellow cake, indicating again the absence of respective studies.**

As all published LCAs on nuclear energy systems to date involve a great deal of assumptions and generic industrial systems data, **the database on the relevant processes should be improved by research in these fields.** For this reason in the present report no numbers are quoted from the reports reviewed. There is a considerable risk that these numbers then would be perpetrated, which would defeat the object of this report, which tries to make a case for more detailed data collection on the subject.

As is clear from the previous discussion, the data needed for a meaningful assessment can only come from the industry itself that actually operates the processes. These data would have to be subject to a careful review procedure in order to ensure that they comply with the agreed upon conceptual system description. **The SET-Plan** (http://ec.europa.eu/energy/technology/set_plan/set_plan_en.htm) **initiative of the European Commission might open an opportunity to tap into data sources, as some of the major industrial players in the nuclear area are involved.** In this case the issue of confidentiality of operational data will arise. While it is understandable that commercial operators have an interest in protection the confidentiality of operational data, it contradicts the concept of making databases that are used in preparing public policy decisions freely accessible to public scrutiny. This dilemma arises in other realms of public decision making support and the solutions found there may be reviewed for their applicability in the present context.

Constraints on U availability other than resources availability

The discovery and exploitation of uranium resources may be subject to a variety of systemic constraints that prevent their quick adaptation to increasing market demands. The past decades have seen a substantial decline of trained personnel at all levels in the raw materials industries. Compared to earlier periods much less exploration took place world-wide and particularly in Europe (metal) mining as such has all but disappeared. Even in a traditionally mining-oriented country such as Australia the boom in uranium exploration over the past couple of years was hampered by the shortage of scientists and engineers trained in this field (P. Waggitt, IAEA, pers. comm.). The situation will be potentially aggravated by the closure of many mining-related university departments around the world. If uranium

production needs to be stepped up again, measures to improve the training situation will have to be taken.

There is also a natural delay between the discovery of an ore body and its full commercial exploitation. Designing, permitting and constructing a mine is a process that will likely take several years. Due to the increasingly difficult licensing and permitting procedure, involving not only the technical side, but also public stakeholders, the time span between license application and the start of operations appears to increase by years.

There is a wide range of other economic and societal risks to a steady uranium supply which are beyond the scope of this report. They have been discussed from a European perspective, for instance, by PRESTON & BARUYA (2006).

Summary and conclusions

The viability of nuclear energy systems that are based on nuclear fission are hinged on the availability of uranium, or thorium, as fuel and on the question whether the overall energy balance of the respective fuel cycle is positive, taking into account the full life-cycle (energy) costs. This report addresses the so-called front-end of the nuclear fuel cycle, which is defined here as to comprise the exploration, the mining and milling of uranium and thorium ores, not forgetting the management of residues arising from these processes. The steps of enrichment and fuel fabrication have been excluded from this report.

When projecting the viability of nuclear energy systems based on fission one also needs to keep in mind that due to process losses less than 80% of the original uranium content of the ore body will actually be available for fuel fabrication.

The availability of uranium as a resource is strongly linked to the energy that needs to be invested to convert the resource into yellow cake. The fundamental question is: how much (fractional) energy units do we need to invest in order to produce one energy unit in a useable form, i.e. heat or electricity. In other words: what is energy cost of providing 1 Joule worth of fuel for the energy conversion system ? Uranium is a fairly common element in the earth's crust, but mineable concentrations do not occur too often. Comparisons with historic mining data for gold and silver lead to the expectation that uranium reserves would increase by orders of magnitude, if the same investment into exploration would be made that has been historically made for these precious metals.

Resources estimates are commonly made on the basis of economic cost to recover the resource. From a global energy supply sustainability point of view neither commercial nor national strategic considerations nor time considerations are really relevant. As oil prices have shown, society can and will accommodate price increases by one order of magnitude over the span of half a century.

A number of so-called 'unconventional' uranium resources have been identified in principle. The most cited include phosphate minerals, residues from coal burning and the seawater. Some of the resources exceed in quantity by far the 'conventional' resources. The energy efficiency of mining these resources is strongly debated in some cases, but very few hard data exist. Possible synergies between the various processes, such as sea-water desalination or fertiliser production, and the recovery of uranium should be investigated from a technological and energy cost point of view. To date there is also no fully quantitative assessment which (historical) residues might be amenable to uranium recovery.

The individual process steps that lead from the undiscovered resource to yellow cake as the marketable uranium product are well established. The energy costs and associated greenhouse gas (GHG) emissions are not very well known in quantitative terms. It is clear, however, that the front-end of the fuel-cycle is one of the biggest net-consumer of energy and emitter of GHGs. Therefore detailed, actual industry data for process energy or life-cycle energy costs should be compiled for the various components of

— exploration
— mining as per type of mining, considering in particular also low-grade ores
— in situ leach (ISL) mining
— milling process

Considering the likelihood that mining will have to move to harder rocks, it would be helpful to have a database available that compares the energies required to breakdown and dissolve the uranium ore from different rock types and mineralisations.

The energy costs for the management of mining and milling residues and environmental remediation of such sites can be considerable. However, to date no assessment of these energy costs has been undertaken anywhere.

Possible scenarios, technical feasibilities and logistics for low-carbon energy supplies to uranium mines and mills could be explored together with the relevant producers.

The SET-Plan initiative of the European Commission might open an opportunity to tap into data sources, as some of the major industrial players in the nuclear area are involved.

Demonstrating an optimal use of resources with minimal environmental impact will help to increase the public acceptability nuclear energy systems.

In summary, it is concluded that a comprehensive assessment of the full-life cycle energy costs of uranium mining, milling and subsequent decommissioning and remediation of the related infrastructure is required. This assessments needs to be based on actual industry data and should comprise both, conventional uranium mining and the utilisation of the so-called unconventional resources. The SNETP consortium would provide a good starting point as it comprises most of the major players of European relevance.

Acknowledgements

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European Commission

Abstract
This report discusses some fundamental sustainability aspects of nuclear energy systems. Sustainability is used here in a broad sense, encompassing economic as well as environmental aspects. As all raw materials, uranium as resource is available in limited quantities only, although it is by no means scarce in terms of abundance in the earth's crust. What can be called a resource is determined by the energy investment that is required to recover it. On one hand this is a simple economic consideration, but on the other hand any energy expenditure has environmental impacts associated with it, including the emission of greenhouse gases. An additional aspect is the relationship between energy investment and net energy gain that may become unfavourable as deeper resources and more refractive uranium mineralisation will have to be exploited.

The report outlines the data needs for a more quantitative and long-term strategic assessment of the availability of uranium as fuel in nuclear energy systems.

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